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Total prompt γ -ray emission in fission

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Abstract. The total prompt γ -ray energy distributions for the neutron-induced fission of ^{235}U , $^{239,241}\text{Pu}$ at incident neutron energy of 0.025 eV – 100 keV, and the spontaneous fission of ^{252}Cf were measured using the Detector for Advanced Neutron Capture Experiments (DANCE) array in coincidence with the detection of fission fragments by a parallel-plate avalanche counter. Corrections were made to the measured distribution by unfolding the two-dimension spectrum of total prompt γ -ray energy vs multiplicity using a simulated DANCE response matrix. The mean values of the total prompt γ -ray energy $\langle E_{\gamma,\text{tot}} \rangle$, determined from the unfolded distributions, are $\sim 20\%$ higher than those derived from measurements using single γ -ray detector for all the fissile nuclei studied. This accounts for a significant fraction of 28% that is the underestimated γ heating from existing data.

1 Introduction

The total prompt γ -ray emission in fission accounts for about 40% of the total energy released by γ -ray emission that makes up about 10% of the total energy released in reactor core. The heating in nuclear reactors attributed to the total γ -ray emission in fission is underestimated up to 28% using the evaluated data for the main reaction channels, $^{235}\text{U}(\text{n},\text{f})$ and $^{239}\text{Pu}(\text{n},\text{f})$ [1]. This discrepancy is significantly greater than 7.5%, an upper bound of the uncertainty deemed necessary to adequately model the heat deposit in the fuel core [2,3]. Therefore, efforts are needed to improve the experimental data on the γ -ray emission in fission. As a matter of fact, the request for the new data on the prompt fission γ rays at thermal energy and above for those two isotopes has been categorized as the high-priority by the Nuclear Energy Agency under the Organization for Economic Co-operation and Development [4]. The majority of measurements made for the prompt γ -ray emission in fission always employed a single or a few γ -ray detectors. For example, a single NaI detector was used by Verbinski *et al.* [5] more than 40 years ago and the cerium-doped LaBr₃, CeBr₃, and LaBr₃ detectors were used recently by Billnert *et al.* [1] and Oberstedt *et al.* [6,7].

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Below we describe the analysis and results on the total γ -ray emission in fission measured by the DANCE array [8,9]. DANCE consists of 160 equal-volume, equal-solid-angle BaF_2 detectors, covering a 4π geometry space, and is located at the Los Alamos Neutron Science Center (LANSCE). Several unique features exhibited by DANCE are particularly attractive for those measurements, such as the nearly γ -ray energy independence for the detection efficiency, the multiplicity response, and the peak-to-total ratio, all of which are described in detail in Refs. [10-12]. For example, it enables one to measure the total γ -ray energy as a function of multiplicity. The only limitation is the energy resolution, which is about 14% for the measured total γ -ray energy. A series of measurements of the prompt γ rays in the neutron-induced fission of ^{235}U and $^{239,241}\text{Pu}$, and the spontaneous fission of ^{252}Cf has been carried out recently using DANCE in coincidence with the detection of fission fragments by a compact parallel-plate avalanche counters (PPAC) [13]. The results on the measured and unfolded fission prompt γ -ray energy and multiplicity distributions for those isotopes have been published [12,14]. An independent analysis of the same data for ^{239}Pu , by assuming a general parameterized correlation between E_γ and M_γ , was presented in Ref. [15]. We also reported the total prompt γ -ray energy distributions for those isotopes, obtained by unfolding the measured two-dimensional spectrum of total γ -ray energy vs multiplicity [16]. This unfolding procedure and the implication on the γ heating in nuclear reactors are described.

2 Experiments and data analysis

The measurements of the prompt γ emission in the neutron-induced fission of ^{235}U and $^{239,241}\text{Pu}$ as well as the spontaneous fission in ^{252}Cf were performed at the Lujan Center of LANSCE. The experimental setup and the data analysis have been described in detail in our early publications [12,14-16]. A brief summary of the experiments is given here. The prompt γ rays emitted in fission were detected by the DANCE array in coincidence with the detection of fission fragments by a compact PPAC [13]. More than 10^6 fission events with at least one γ ray detected by DANCE were collected for all isotopes studied. The threshold for detecting γ -ray energy by DANCE was set to 150 keV. A gate on the pulse height spectrum of PPAC in addition to the 8-ns gate on the time spectrum between PPAC and DANCE was placed for the final analysis. All the offline data analysis was carried out using the code, FARE [17]. Note that the total γ -ray multiplicity (M_γ) in fission is established not according to the number of detectors observing the γ ray, but instead according to the number of clusters by grouping adjacent detectors catching the γ ray in the same time window. This counting method for M_γ is to avoid the overcounting because of the Compton event and is closer to the simulated results using the γ -ray calibration sources [10-12].

Corrections have to be made to the measured $E_{\gamma,\text{tot}}$ distribution to obtain the physical distribution, which would be useful for the applications. This can be accomplished by unfolding the two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs M_γ . It is numerically implemented by adopting the iterative Bayesian method [18-20]. The DANCE response matrix for $E_{\gamma,\text{tot}}$ vs M_γ is simulated using the GEANT4 [21] geometrical model of both DANCE and PPAC [12,14,22]. To make sure this two-dimensional response matrix has a sufficient coverage of the phase space beyond the measured one, the value of M_γ up to 25 and $E_{\gamma,\text{tot}}$ up to 40 MeV are included. The $E_{\gamma,\text{tot}}$ has a bin size of 200 keV and an energy threshold of 150 keV. So the response matrix has a size of 200×25 .

For any given grid point ($E_{\gamma,\text{tot}}$, M_γ) in the response matrix, a two-dimensional DANCE response matrix of a size of 200×25 is generated using GEANT4 with an assembly of no more than 20,000 samples. Note that the DANCE response to the total prompt γ -ray is relatively insensitive to the content of γ rays for a given sample since the γ -ray detection efficiency (84 to 88%) and the peak-to-total ratio ($\sim 55\%$) remain nearly constant for the γ -ray energy ranging from 150 keV to 10 MeV [10-12]. Each sample has a matching number of γ rays to M_γ , selected randomly according to the unfolded γ -ray energy distributions [12,14] with the condition on the total γ -ray energy that is equal to $E_{\gamma,\text{tot}} \pm 100$ keV. This simulation is repeated for all the grid points within the lower and upper bound of $E_{\gamma,\text{tot}}$ for a given M_γ , established by this random sampling technique.

The resulting ($E_{\gamma,\text{tot}}$, M_γ) DANCE response matrix consists of ~ 3300 two-dimensional matrices with a size of 200×25 each. This numerically simulated DANCE response matrix is unique for each isotope studied, and was used to unfold the measured two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs M_γ into a physical one using the iterative Bayesian method. During the iteration stage, a single factor was applied to and varied for the response matrix at any given grid point.

3 Results and discussions

Typically it takes about 30 iterations to reach the convergence in the unfolding of the two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs M_γ using the iterative Bayesian method. The comparison of $\langle E_{\gamma,\text{tot}} \rangle$ between our measurements and previous ones is given in Table 1. For ^{235}U , the recent (2-D) derived mean $E_{\gamma,\text{tot}}$ of 8.35 MeV is higher than 6.53(20) MeV, the weighted average of previous measurements [23], and 6.60 MeV, the evaluated data listed in ENDF/B-VII.1. It also is higher than 6.92(9) MeV, the most recent measurement [6]. The same comparisons are also made for the neutron-induced fission in $^{239,241}\text{Pu}$ and the spontaneous fission in ^{252}Cf . Our measured $\langle E_{\gamma,\text{tot}} \rangle$ are consistently higher than the previous ones [1,6,7,23] by $\sim 20\%$ for all isotopes studied. The uncertainty for our derived $\langle E_{\gamma,\text{tot}} \rangle$ is dominated by the systematic error and roughly estimated to be better than 5%, assuming a similar uncertainty to that of the derived $\langle M_\gamma \rangle$.

Table 1. Comparison of the mean $E_{\gamma,\text{tot}}$ (MeV) between our recent measurements and previous ones for the neutron-induced fission of ^{235}U and $^{239,241}\text{Pu}$ as well as the spontaneous fission of ^{252}Cf .

Isotope	2-D	Ref. 15	ENDF/B-VII.1	Ref. 23	Refs. 1, 6, 7
^{235}U	8.35		6.60	6.53(20)	6.92(9)
^{239}Pu	7.94	7.46	6.74	6.78(10)	
^{241}Pu	8.01		7.26		6.41(6)
^{252}Cf	8.52			6.95(30)	6.64(8)

4 Summary

A systematic study of the total prompt γ -ray emission in the neutron-induced fission of ^{235}U and $^{239,241}\text{Pu}$ as well as the spontaneous fission of ^{252}Cf has been carried out using the DANCE array together with a compact PPAC to select the fission event by detecting its fission fragments. The total γ -ray energy vs multiplicity spectrum for all fissile nuclei studied was constructed and unfolded using a two-dimensional unfolding technique,

numerically implemented by adopting the iterative Bayesian method. The $\langle E_{\gamma,\text{tot}} \rangle$ derived from the projected $E_{\gamma,\text{tot}}$ distribution of the unfolded $E_{\gamma,\text{tot}}$ vs M_γ spectrum is about 20% higher than the previous measurements for all fissile nuclei studied. This accounts for a significant fraction of 28% that is the underestimated γ heating from existing data.

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